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OFFICE NOTE 337

THE IMPACT OF LESS FREQUENT CALCULATIONS OF VERTICAL AUSTAUSCH AND PRECIPITATION ON FORECASTS FROM THE NESTED GRID MODEL

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ABSTRACT

Forecasts with the Nested Grid Model were made in which the interval between calculation of (vertical mixing plus precipitation) were varied from 1.25 minutes to 60 minutes on grid C. As the interval is lengthened, the convective precipitation in a fixed time (e.g. 12 hours) increases, but the grid-scale precipitation decreases more, resulting in a decrease of precipitation. Small decreases in cyclogenesis are noted when the interval is long. These effects are not present when only the vertical mixing interval is lengthened.

Thought could be given to reducing this effect on precipitation by adding an anticipatory estimated effect every dynamical time step.

1. Background

The original version of the Nested Grid Model (NGM) did the "dynamical" calculations and the "physical" calculations for a single time step (on one of the grids) in a sequence in which the two effects were intermingled.[1] This was the most computationally efficient way for the code as it then existed, without radiation. It was recognized in 1985 that when additional physics were added (i.e. radiation) greater computational efficiency (as well as a more understandable code) might be achieved if the two types of calculations were not intermixed in the same subroutine . This reprogramming was carried out in 1985 and 1986. On December 9 1987 it enabled a moderate speed-up to be implemented in the non-radiational part of the system by performing the physical calculations less often . This Office Note examines some of the effects of less frequent computations of vertical austausch and precipitation.

The basic procedure used in the dynamics part of the NGM is a "two-step" Lax-Wendrof procedure (Phillips, 1960 and 1979). This was accomplished in the original version by the following symbolic scheme to advance the forecast variables X from time step $t = n\,\Delta t$ to time step $t = (n+1)\,\Delta t$:

$$X_{n+1/2} = X_n + \frac{\Delta t}{2} [D(X_n) + F(X_n)] , \qquad (1.1)$$

$$X'_{n+1} = X_n + \Delta t [D(X_{n+1/2}) + F(X_n)] , \qquad (1.2)$$

where D represents the "dynamical" effects - advection, pressure force and Coriolis force-- and F represents the effect of turbulent vertical exchange. The final step was that of precipitation

$$X_{n+1} = X'_{n+1} + P(X'_{n+1} ; X'_{n+1} - X_n) . \qquad (1.3)$$

(The second argument in the precipitation operator P represents the water accumulation amount that is redistributed vertically in the Kuo convective algorithm. Details of the precipitation calculations are given in the appendix.)

All three operations were exercised in the original form of the NGM code in succession at a time interval Δt that was set by the von Neumann computational stability criterion

$$(C_{ext} + |V|) \Delta t < \Delta s \qquad (2)$$

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[1] Dynamical means the processes of advection, pressure gradient force and Coriolis force. "Physical" includes turbulent mixing, precipitation, and radiational heating.

determined by the external gravity wave speed $C_{ext} \sim$ 320 meters/second, a maximum particle speed $|\underset{\sim}{V}|$ of about 100 meters/second, and the horizontal space increment Δs for each grid. In the current operational three-grid format this results in the following time steps.

$$\text{Outer grid A:} \quad \Delta t_A = 300 \text{ secs} = 5 \text{ mins} \tag{3.1}$$

$$\text{Intermediate grid B:} \quad \Delta t_B = 150 \text{ secs} = 2.5 \text{ mins} \tag{3.2}$$

$$\text{Inner grid C:} \quad \Delta t_C = 125 \text{ secs} = 1.25 \text{ mins} \tag{3.3}$$

These time steps (especially on grid C) are short compared to the time scales that can be associated with two of the physical processes.

<u>Convection</u>: The buoyancy frequency in a normally stable atmosphere surrounding convection will be

$$\frac{g}{T}\left(\frac{g}{C_p} + \frac{dT}{dz}\right) \sim \left(\frac{2\pi}{10 \text{ mins}}\right)^2 \tag{4.1}$$

Only grid C would have Δt short compared to 10 minutes, however.

<u>Vertical diffusion of momentum</u>: Time scale = (boundary layer depth)^2 / ν

$$\sim \text{(Ekman layer depth)}^2 / \nu$$

$$= (\nu / f) / \nu = 1/f$$

$$= 3 \text{ hours} \tag{4.2}$$

This suggests that turbulent vertical diffusion and <u>perhaps</u> precipitation need not be calculated as frequently as defined by (3.2) and (3.3).

In anticipation of this, the code embodying (1.1)-(1.3) was first restructured in 1986 to allow the following schedule of calculations.

Dynamics:

$$X_{n+1/2} = X_n + \frac{\Delta t}{2} D(X_n) \tag{5.1}$$

$$X'_{n+1} = X_n + \Delta t \; D(X_{n+1/2}) \tag{5.2}$$

Vertical exchange:

$$X''_{n+1} = X'_{n+1} + \Delta t \;\; F(X_n) \tag{5.3}$$

Precipitation:

$$X_{n+1} = X''_{n+1} + P(X''_{n+1} \; ; \; X''_{n+1} - X_n) \tag{5.4}$$

This is now a "split" computation method. The major difference from the original scheme (1.1)-(1.3) is the important step of being able to disregard the vertical austausch terms in (1.1). This was tested satisfactorily in early 1986, and the basic method (5.1)-(5.4) was implemented in April 1986. The frequency of all computations at that time, however, was maintained at the original rate set by (3.1)-(3.3).

In July 1986, a radiation code was added to the NGM. (See NWS, 1986). At that time these calculations were done at the following intervals.

a. The contribution of the flux of infra-red radiation to $\partial T/\partial t$ was recomputed every hour.
b. The contribution of the flux of short-wave radiation to $\partial T/\partial t$ was recomputed every hour.
c. The surface temperature of the ground was updated every 300 seconds (i.e., every grid A time step).

These radiation calculations produced a cold bias almost everywhere. A correction for this was implemented in late October 1987, by restoring every hour the hemispheric averaged potential temperature on each sigma surface to its initial value. Mean temperature errors in the midtroposphere are now slightly positive in the eastern United States, but still negative in the western United States. This decreased precipitation amounts by about 10 percent. (NWS, 1987) The shrinkage of the area enclosed by the rain/no rain contour reduced the previous excessive rain coverage in the NGM to a very acceptable value.

In late 1987, J. Tuccillo tested the ability of the system (5.1)-(5.5) to yield similar forecasts when the interval for updating the infra-red radiation, vertical turbulent exchange and precipitation was lengthened to an integral number of the grid-based time steps. The "splitting" of the precipitation effects can be done in several ways.

METHOD A. Calculate the precipitation-induced change over one time interval (Δt) at every n-th time step, and simply add these identical changes at time steps n, n+1, n+2,---, through time step 2n-1. At this time, the Δt-sized precipitation induced change would be recomputed for insertion in the next n time steps. This amounts to an extrapolation of the computed amounts. It has the disadvantage that the separate budgets of water and enthalpy are not satisfied.

METHOD B. Calculate the precipitation-induced change over n time intervals at every n-th time step. Add these changes to T and q at that time, but add no more precipitation-induced changes until time step 2n. The individual budgets of water and enthalpy will be satisfied in this procedure, but it will provide more of a shock to the system.

Both of these methods require the storage of new fields. In METHOD A, one must save the individual Δt-sized changes in both T and q, whereas in METHOD B, one must save the fields of q at time step n. A third method (which would require the saving of three fields) would be to use METHOD A, but to also save the field of q from the end of each n-th time step, so that a more exact allowance for the budgets could be made at the next n-th time step.

Tuccillo used METHOD B. He found the following results.

a. Little noticeable change in forecast occurred when the infra-red radiation was recomputed every two hours instead of every one hour.
b. Some decrease in precipitation, mostly in the maximum amounts, was noted when the interval between calculations of vertical exchange and precipitation was lengthened to 15 minutes on all grids.
c. Each of these actions saved about 20% of the CPU time of the forecast part of the NGM system.

A major portion of the speed-up from action b came when that interval was increased to 5 minutes on all three grids, thereby doing the calculations on grid C only 1/4 as often. A scheme was implemented on December 9 1987 in which the infra-red calculations were done every two hours, and the calculations of vertical turbulent exchange and precipitation were done every 15 minutes.

The remainder of this Office Note documents tests of one forecast case in which only the time interval between calculating (vertical mixing plus precipitation) were changed. All other aspects of the NGM forecast system were held fixed in these tests.

2. The forecasts from 00Z December 14 1987

This case was selected because the operational forecasts using the new speeded-up code were good.[1] Figure 1 shows the initial sea-level pressure map, together with the operational 48-hour forecast and the verifying map at 00Z on December 16. Figure 2 shows the 24-hour precipitation amounts for the period 12Z 14 Dec through 12Z 15 Dec, as forecast and as observed. The principal observed features (after much mental smoothing of the results) consist of a band from northwestern Arkansas to Detroit (with a minor axis through Kentucky), plus a separate line from the Gulf Coast of Alabama north-northeastward into southwestern North Carolina.

Forecasts were made with the following interval for splitting. (The code structure is such as to accommodate a choice of splitting length most easily if all vertical mixing is handled together with precipitation as a single package.)

Interval for calculating vertical austausch and precipitation.	Interval for Grid C	Normalized interval for Grid C
Δ t of grid (i.e. no splitting)	1.25 minutes	1
5 minutes (= Δ t for grid A)	5	4
10 minutes	10	8
15 minutes (the new operational value)	15	12
30 minutes	30	24
60 minutes	60	48

[1] A small eastward displacement of the forecast would be beneficial, in keeping with the NGM tendency for a slight underforecast of phase speed. A more telling criticism is that the observed precipitation field on Figure 2 represents a high percentage of convective rain, whereas Table 1 shows that most of the model precipitation was not convective. This incorrect partitioning of precipitation is probably not unusual in current NWP models.
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The most significant change that occurred was in the precipitation amounts. Table 1 shows the sum over all points on the forecast grid C of the 12-hourly amounts of convective, grid-scale, and total precipitation.[1] We see that

a. Increasing the interval increases the amount of convective rain.

b. Increasing the interval decreases the amount of grid-scale rain.

c. The decrease in grid-scale rain over-balances the increase in convective rain, so that the net result of increasing the interval is to decrease the total rain.

The interplay between a and b follows conventional experience. (The convective precipitation calculations in the NGM, as in other models, is intended to be a stabilizing process, accomplishing this by preventing the occurrence of supersaturated air with an unstable moist-adiabatic lapse rate, and, by moving upward the effective layers in which latent heat is released, reducing the positive feedback between saturation and low-level convergence. An enhancement of the role of convection therefore results in <u>less</u> precipitation and <u>reduced</u> cyclogenesis.)

It remains to explain why the convection rain is increased when the splitting interval is lengthened. The answer to this can be seen in Table 2. This Table compares the number of points on grid C that met the three successive criteria for convective precipitation (see the Appendix), for the extreme cases of no splitting and a 60-minute interval for splitting.

The dominant effect of the 60-minute splitting is to increase the number of columns that have buoyancy at some level; little change is made in the number of points that meet the first criterion of a modicum of moisture increase, or in the number of columns that have net accumulation when summed over the layers up to and including the uppermost buoyant layer. One explanation of the increase in unrealized moist instability at the beginning of the precipitation calculations is that the lifting condensation level has been lowered by an increased relative humidity in the lower layers, and that this results in a warmer cloud column. A second explanation might be that a more unstable lapse rate exists at the beginning of the precipitation calculations when the latter were performed less frequently. (The destabilizing of the column of grid-point temperatures can be due to mid-tropospheric cooling from infrared radiation, or to a maximum of warm air advection in the lower tropospheric layers in the cyclone in the central United States.) [2]

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[1] Sums were also computed separately for land and for ocean points; they showed the same patterns and therefore only the total sums are shown in Table 1. A rough calibration of intensity can be obtained by division of the total amounts by 2000, a typical value for the number of points with precipitation shown on Table 2. Thus a value of 10 in the "No Split" column of Table 1 corresponds to 10/2000 = 0.005 meters = 0.5 centimeters, or about 0.2 inches.

[2] The converse of this is to simply reverse the order of convective and grid-scale precipitation that is described in the Appendix; the convective precipitation almost disappears if it is computed after the grid-scale process.

These changes in convective and grid-scale precipitation seem to have occurred mostly in regions of significant precipitation. This is shown most clearly by Figure 3, contrasting the 36-hour precipitation fields obtained with "No Split" and with a 60-minute splitting interval. The outlines of the rain areas (defined graphically by amounts more than 0.01 inch) are almost identical.

Table 1 shows that the amount of precipitation forecast on Figure 2 would have been increased by perhaps 10%, if the forecast had been made without splitting. The observed amounts on Figure 2 are too irregular to reach a clear conclusion as to whether this would have been desirable, but there is a hint that a slight increase in forecast precipitation would be beneficial.

The lengthened interval between precipitation calculations does not seem to have introduced noise into the forecast. Table 3 summarizes the root-mean-square value of $d\sigma/dt$, summed over all levels and forecast columns on grid C. A slight decrease is noted, in fact, with a lengthening of the splitting interval.[1]

A slight effect on the sea-level pressure forecast was noted, in that the forecast low center at 48 hours in upper Michigan had the following values:

Split interval for grid C(mins):	1.25	5.0	10.0	15.0	30.0	60.0
48-hour value	989	989	989	989	990	992

All of the above effects are consistent with the experience of J. Tuccillo from the studies he made before implementing the speeded-up split version of the NGM on December 9 1987.

Some consideration might be given to minimizing these effects on precipitation by exploring the more expensive METHOD A described on page 3.

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1 This stability might not be so strong for numerical integration methods that are less well-behaved than the Lax-Wendroff type used in the NGM. The "observed" value of 984 millibars suggests that splitting, by reducing the amount of grid-scale precipitation, reduced the cyclogenesis. In this case this would be in the wrong direction.

3. Longer intervals for vertical mixing of momentum.

The above computations have been done by treating the effects of surface mixing (of moisture and temperature) , vertical austausch mixing of momentum, and precipitation, as a single package. The earlier discussion about time scales suggested that it may be only the vertical momentum mixing that can be postponed to longer intervals without changing the NMG forecasts. A test was therefore made in which the only the vertical austausch mixing of momentum was calculated at 30 minute intervals while the surface mixing and precipitation were performed at each time step for each grid.

The results were almost indistinguishable from the "No Split" case where the vertical momentum mixing was also done at each time step; the precipitation amounts in Table 1 agreed to 0.01 inches, and the column counts in Table 2, differed by less than 1 in several hundred with those listed under "No Split" .

Therefore, all of the effects on precipitation documented and explained in section 2 were due to the longer intervals between precipitation calculations, and not due to longer intervals between the unsaturated vertical mixing processes.

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Table 1. 12-hour precipitation amounts. Values listed under "No split" are the raw precipitation amounts (meters, as a sum over all grid C forecast points) when no splitting is done. Values listed under the remaining columns are the ratio of the precipitation amounts for that splitting interval, divided by the amounts shown under "No split". Values include both land and ocean points on the forecast grid C.

CONVECTIVE PRECIPITATION

Forecast Hour	No Split	5 min	10 min	15 min	30 min	60 min
12	2.35m	1.02	1.07	1.10	1.17	1.16
24	2.80m	1.07	1.13	1.16	1.24	1.25
36	2.24m	1.16	1.21	1.21	1.20	1.23
48	3.01m	1.08	1.08	1.06	0.97	0.98

GRID-SCALE PRECIPITATION

Forecast Hour	No Split	5 min	10 min	15 min	30 min	60 min
12	4.54m	0.81	0.74	0.70	0.62	0.56
24	7.93m	0.89	0.83	0.79	0.71	0.65
36	8.21m	0.88	0.85	0.83	0.78	0.72
48	6.32m	0.90	0.86	0.83	0.78	0.73

TOTAL PRECIPITATION

Forecast Hour	No Split	5 min	10 min	15 min	30 min	60 min
12	6.89m	0.88	0.85	0.83	0.81	0.77
24	10.72m	0.93	0.91	0.89	0.85	0.80
36	10.45m	0.94	0.93	0.91	0.87	0.82
48	9.33m	0.96	0.93	0.91	0.84	0.81

Table 2. Number of grid columns participating in convection calculations at various stages in the NGM Kuo process. Results are shown at each forecast hour for the non-split result (NS) and for the 60-minute split result (60). The last column shows the number of forecast columns in which grid-scale precipitation occurred.

Forecast Hour	Procedure	Forecast columns with crit. accum.	and with buoyancy	and with net accumulation	Forecast columns with grid scale pcpn.
1	NS	1194	545	526	1085
	60	1196	665	651	1143
12	NS	1380	608	583	1912
	60	1400	799	777	1922
24	NS	1375	627	574	2055
	60	1365	797	751	1984
36	NS	1211	540	488	2451
	60	1241	714	651	2554
48	NS	1176	479	431	1888
	60	1185	558	528	1995
Total	NS	6336	2799	2602	9391
	60	6387	3533	3358	9598
	Diff.	51	734	756	207

Table 3. RMS value of $d\sigma/dt$, land and ocean.

Forecast Time	No Split	5 min.	10 min.	15 min.	30 min.	60 min.
	<------------------	frequency	of physics	---------->		
12 hours	8.1×10^{-6}	8.1×10^{-6}	8.1×10^{-6}	8.0×10^{-6}	8.0×10^{-6}	7.9×10^{-6}
24 hours	7.6	7.5	7.5	7.5	7.4	7.3
36 hours	6.7	6.6	6.6	6.5	6.4	6.2
48 hours	6.1	6.0	5.9	5.8	5.7	5.5

Table 4. CPU time to make a 48-hour forecast (includes processing of output fields, but does not include processing of fields before the start of the forecast.)

Frequency of doing "physics"	CPU time	Saving
Every time step	28.0 minutes	0 minutes
5 minutes	22.3	5.7
10 minutes	20.4	7.6
15 minutes	19.8	8.2
30 minutes	19.2	8.8
60 minutes	18.9	9.1

APPENDIX

Steps in precipitation calculations in the Nested Grid Model.

Let Dt denote the time that has elapsed since the previous computation of precipitation for the particular grid being considered.

Define DHQ as the change in the product:

surface pressure in bars times the specific humidity,

that has occurred at each grid point and level since the last precipitation computation :

$$DHQ = [p_{sfc}\, q\,](t) - [p_{sfc}\, q\,](t-Dt) \quad \text{in bars} .$$

DHQ includes the effects of three-dimensional advection, evaporation from the surface, and vertical turbulent mixing.

I. <u>The normal procedure is to calculate first the effect of "convective precipitation"</u>. This occurs in a grid-point column only if three criteria are met.

1. The first criterion is that the grid point be one for which the normal variables must be forecast (i.e., it is not a point close to a lateral boundary), and that the processes included in DHQ are moistening the lower part of the column at a significant rate . This is measured by requiring that

$$\sum_{k=1}^{4} DHQ_k \;/\; Dt \;\geq\; 10^{-8} \text{ bars per second} .$$

2. The second criterion is a measure of parcel instability. For each column passing criterion 1 above, a cloud profile is defined by lifting parcels from each of the bottom 4 layers of the model, first to their lifting condensation level, and then moist-adiabatically upward. The warmest such profile is defined as the cloud profile (T_c, q_c) for that column. A column is eliminated from consideration for convection if there is no level at which T_c exceeds T . For the qualifying columns, the "top" of the cloud is in layer k_{top} , the highest layer at which T_c exceeds T .

3. The third criterion is a more precise measure of moistening. In each of the remaining columns, the vertical integral of DHQ is computed :

$$\overline{DHQ} = \sum_{k=1}^{k_{top}} DHQ ,$$

and all columns for which $\overline{DHQ}$ is non-negative are eliminated.

The convective computation at the remaining columns then proceeds in the usual Kuo method. The enthalpy represented by $L \times \overline{DHQ}$ is split between moistening and heating of the column:

$$\sum_{k=1}^{k_{top}} d(p_{sfc}\, q) = b\ \overline{DHQ} , \qquad \sum_{k=1}^{k_{top}} d(p_{sfc}\, T) = (1-b)(L/C_p)\ \overline{DHQ},$$

where b has at present the value 0.2 . The changes $d(p_{sfc}\, q)$ and $d(p_{sfc}\, T)$ are distributed vertically within the column according to the differences in q and T between the cloud sounding and the existing profiles of q and T ; at each level the adjusted value of $p_{sfc}\, q$ is

$$(p_{sfc}\, q)_{adj}(t) = (p_{sfc}\, q)(t-Dt) + d(p_{sfc}\, q)$$

The appropriate increase to $p_{sfc}\, T\ (t)$ is made to allow for the contribution at that level to the condensed water.

Finally, at each level, beginning with k_{top} and proceeding downward, the values of liquid water corresponding to the heating term are added to a downward current of convective rain. If the relative humidity in a layer is less than 50% /(1+ Δ), enough water will be evaporated from this current to raise the relative humidity in that layer to that value. (The corresponding wet-bulb decrease is made in the temperature of that layer.)

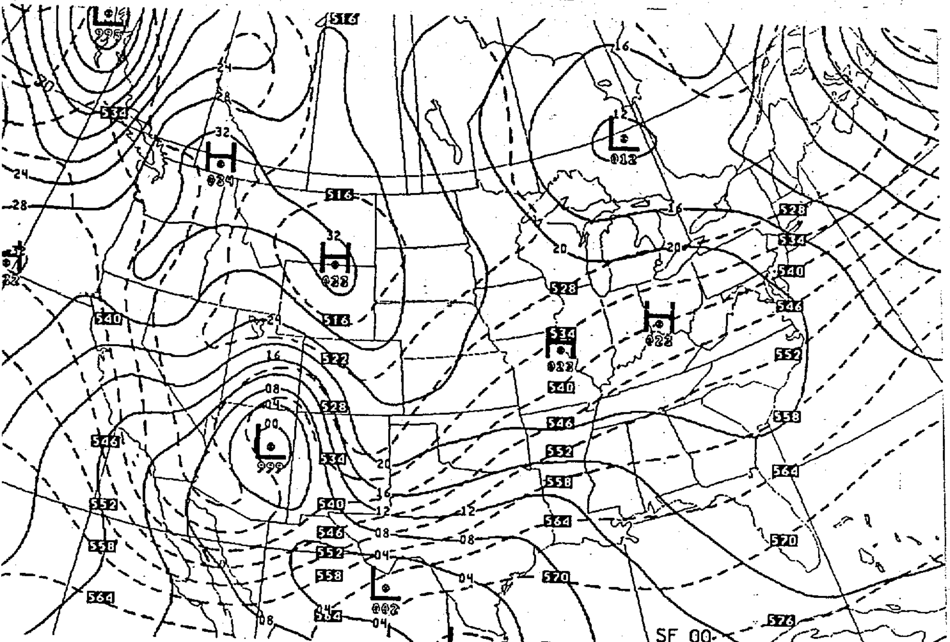
II. Grid-scale precipitation. All grid points are considered except those that are too close to lateral boundaries. The precipitation is computed by a wet-bulb adjustment process at all grid points for which the specific humidity satisfies the criterion

$$q > q(sat) / (1 + \Delta) .$$

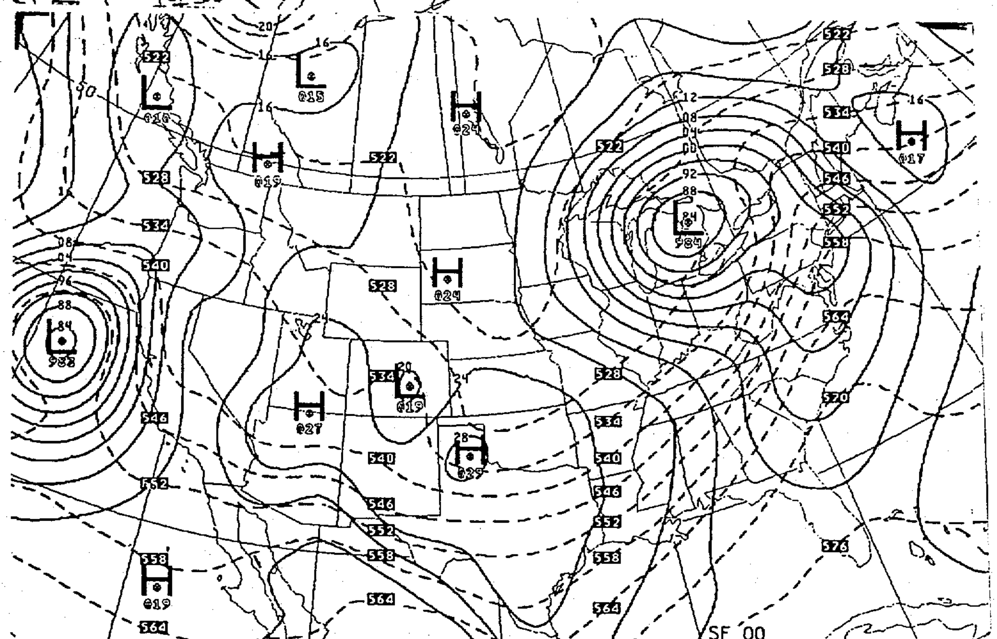
where Δ has the value 0.05 . Details of the calculations are based on the assumption that the specific humidity within a grid box is distributed uniformly within the range

$$(1-\Delta)\, q_{gp} \leqslant q \leqslant (1+\Delta)\, q_{gp} ,$$

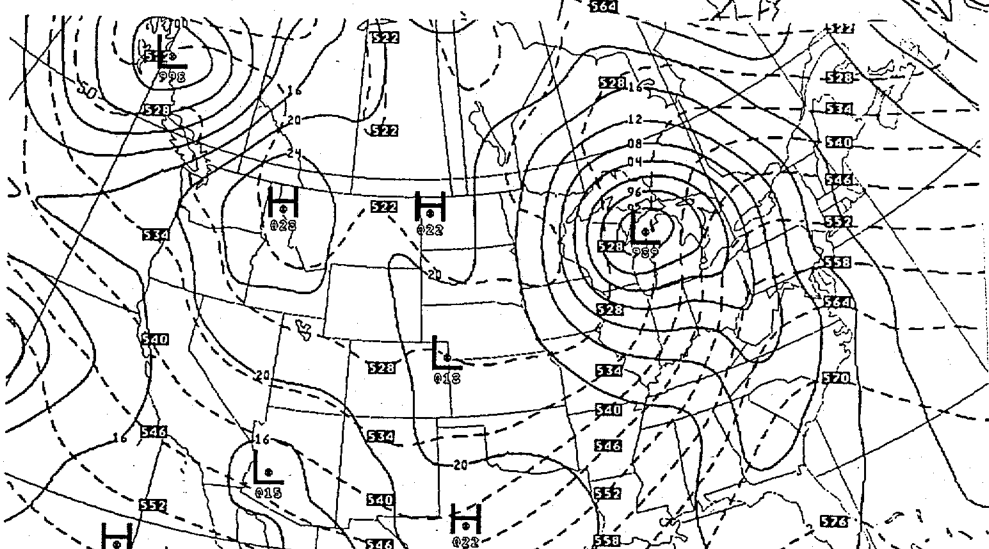
centered about the explicit grid-point value q_{gp} (Phillips, 1981; Hoke, 1982) This type of precipitation is also allowed to evaporate, as with the convective precipitation, except that the saturation criterion is 100% /(1+ Δ) .



Initial
00Z
14
Dec
1987

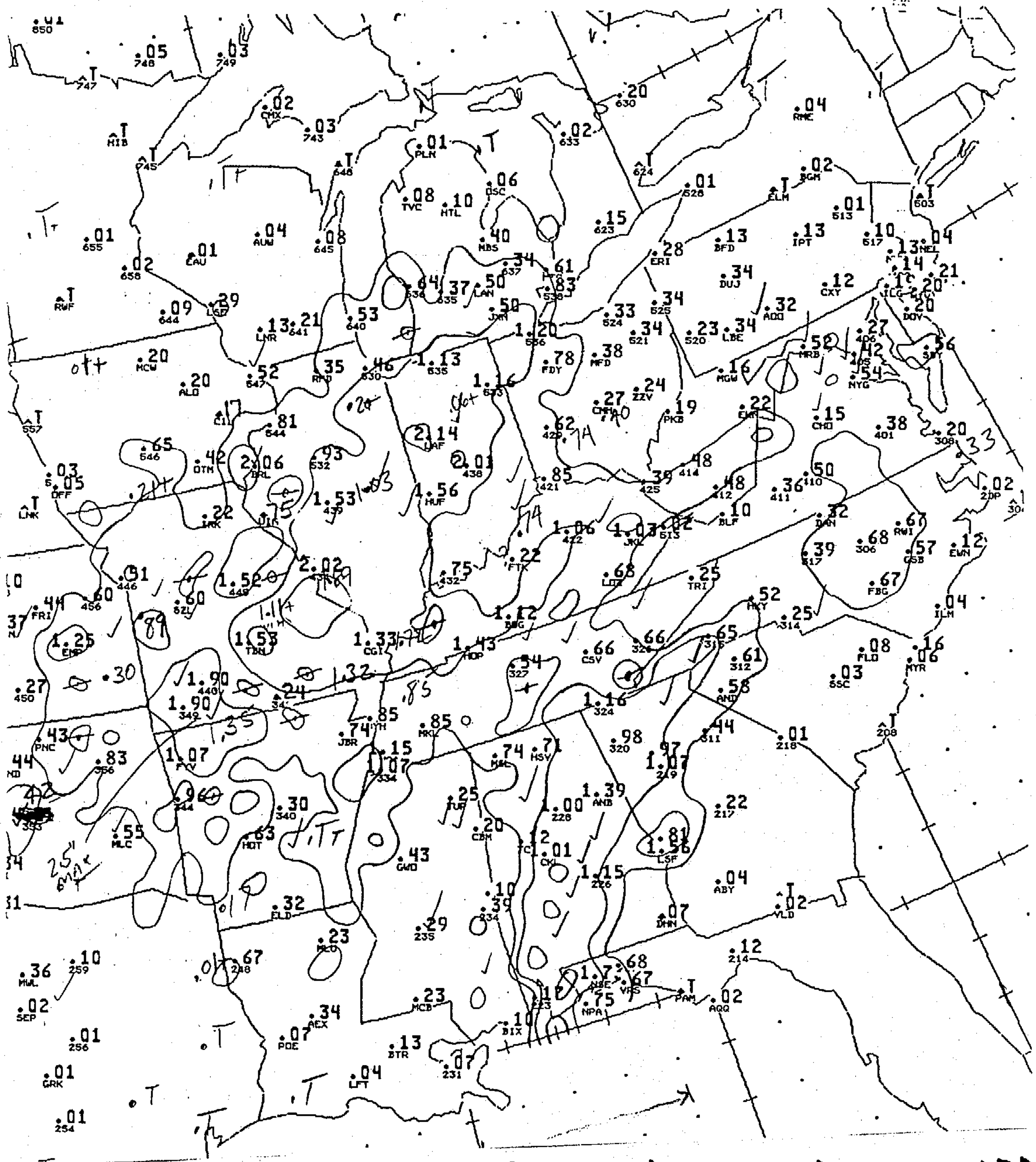


Verifying
00Z
14
Dec
1987

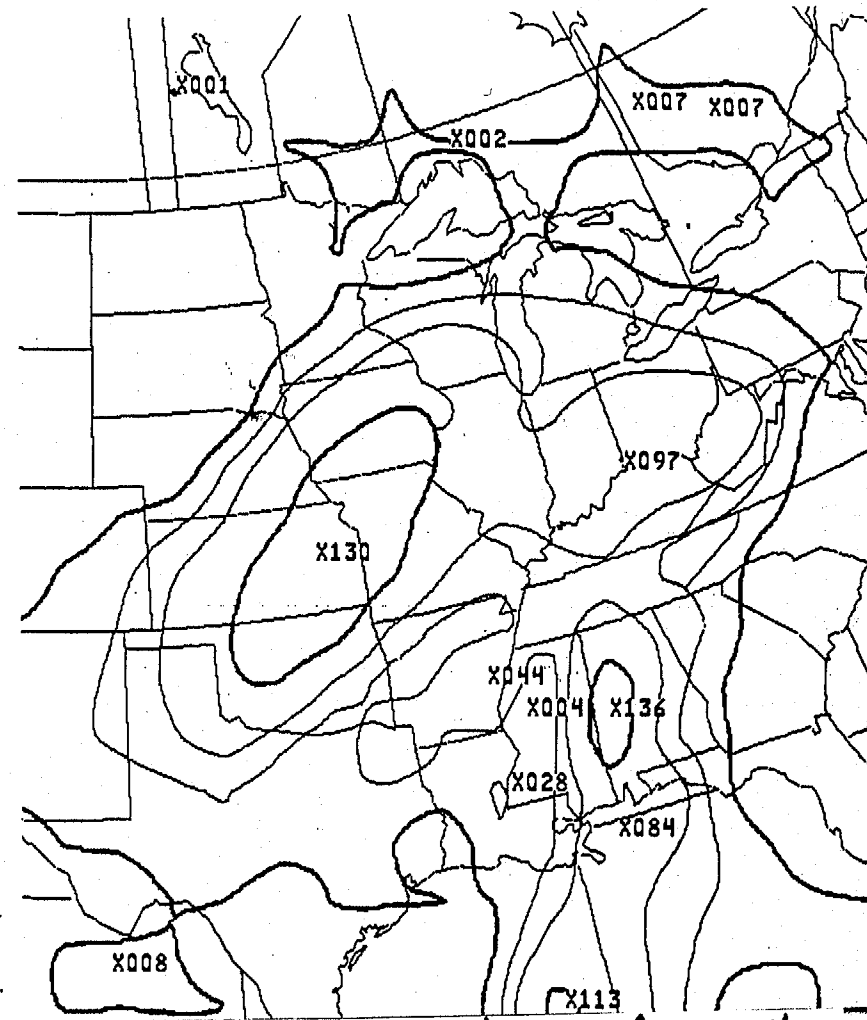


48-hour forecast
(operational)
from
00Z
14 Dec 1987

Figure 1. Sea-level pressure fields

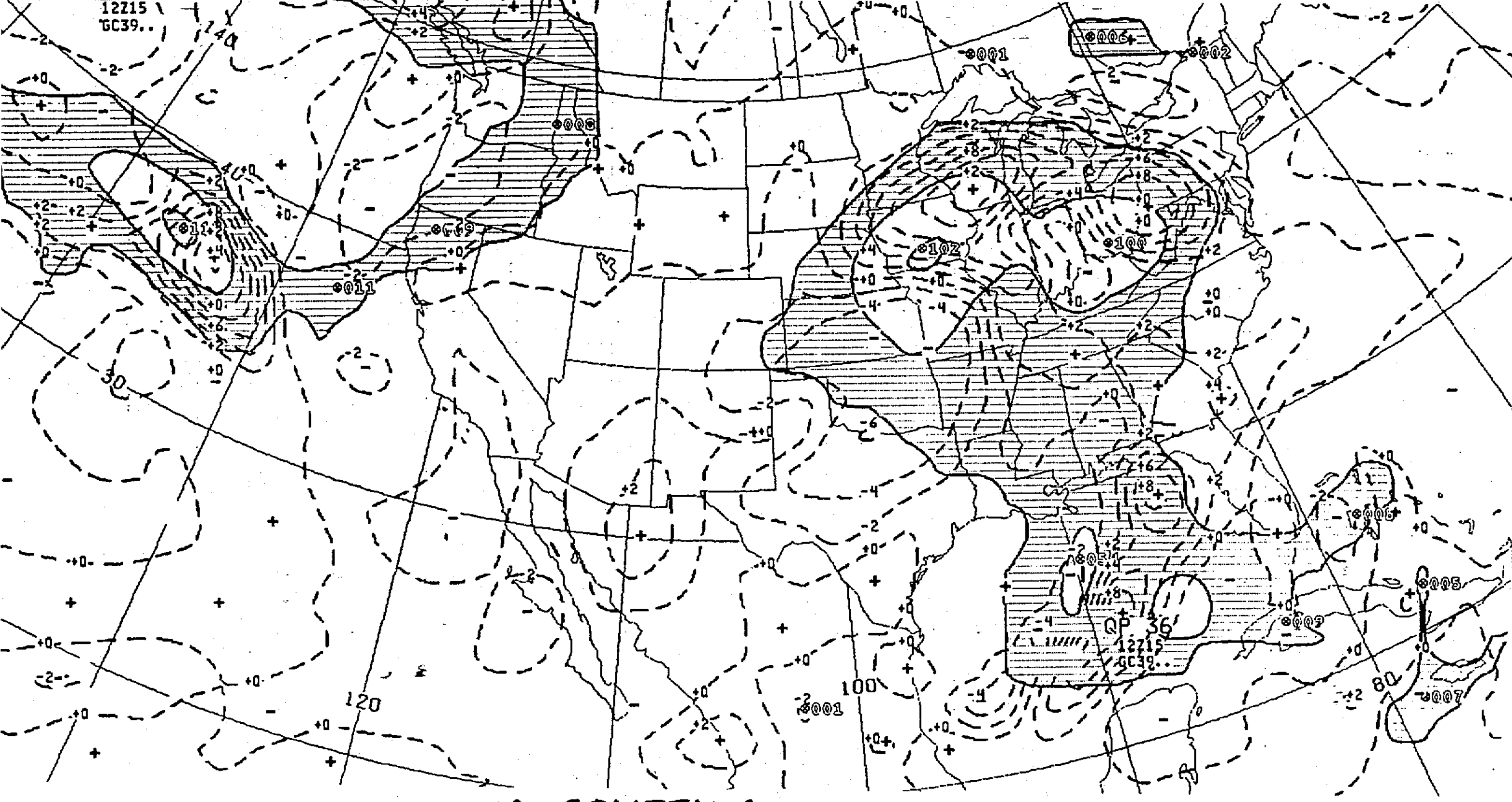


Observed (inches) 12Z 14 Dec - 12Z 15 Dec 1987

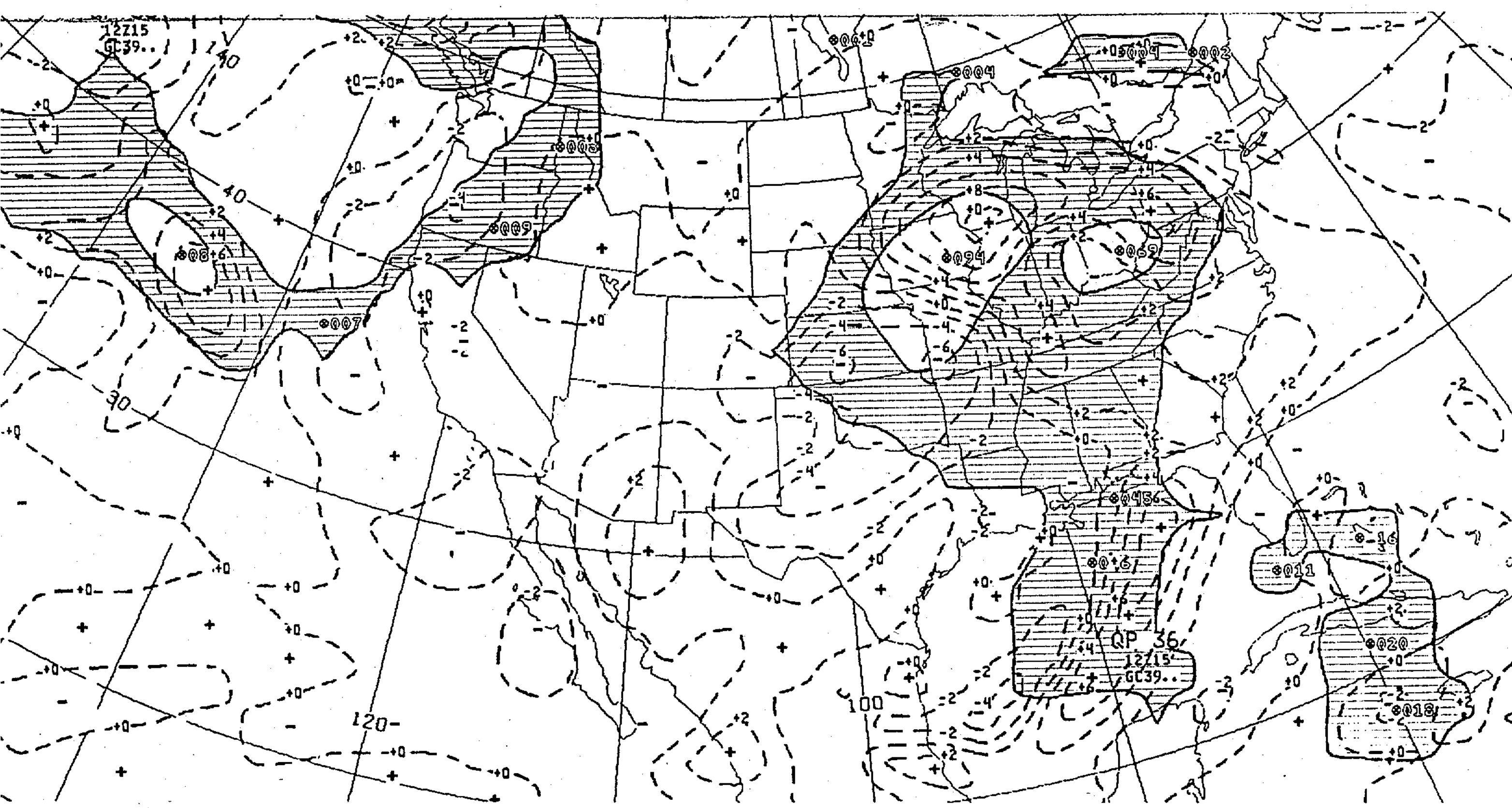


12-36 hr NGM operational forecast (.01 inches) 24-hour precipitation amounts

Figure 2.



NO SPLITTING



60-MINUTE SPLITTING

Figure 3. 12-hour precipitation amounts forecast for the period 00Z-12Z 15 Dec. 1987 from 00Z 14 December.